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Multidimensional echocardiography
An appraisal of its clinical usefulness

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Multiscan is a new concept in echocardiography providing instantaneous cross-sections of the heart in motion without distortion. The examination technique and the present display and recording methods are described and discussed in some detail.

Multiscan provides important anatomical and functional information in the non-invasive diagnosis of congenital malformations and of valvular heart disease. The size, shape, and overall function of the left ventricle can be assessed.

Localized disorders of wall motion are also detected, making the instrument useful for the study and follow-up of patients with coronary artery disease.

Quantitative measurements of cardiac dimensions and calculation of left ventricular volumes using the area-length method can be obtained. From the results presented in this paper one may conclude that the concept of Multi-element echocardiography is a valuable extension of the now widely accepted single element technique and offers vast possibilities for the screening, study, and follow-up of patients with cardiac disease.

Echocardiography is now established as a unique non-invasive diagnostic aid for many congenital and acquired cardiac diseases (Gramiak and Shah, 1971; Feigenbaum, 1972; Meyer and Kaplan, 1973; Popp and Harrison, 1973). However, in most studies where single element probes are used, only a selected, narrow, portion of the heart is explored in depth and recorded as a function of time (time-motion or M-mode). Therefore, no direct information about the anatomical relations of specific cardiac structures or about the activity of the heart as a whole is available. Yet, the importance of and the need for a multi-dimensional echographic display of cardiac structures has been demonstrated by the many attempts over the last few years to visualize the entire cardiac configuration with its true anatomical relations (Äsberg, 1967; Ebina *et al.*, 1967; King, 1973; Kikuchi and Okuyama, 1970; Hertz and Lündström, 1972; Gramiak, Waag, and Simon, 1972). Such a cross-sectional image should afford great advantages in the study of patients with valvular and congenital malformations. In addition, it would allow determination of the ventricular volumes and wall motion. Techniques described so far, however, produce 'frozen' images of the heart (Ebina *et al.*, 1967; King, 1973; Kikuchi and Okuyama, 1970) or have limited frame rates (Äsberg, 1967; Hertz and Lündström, 1972; Gramiak *et al.*, 1972). In fact, real time information about the dynamic function of the heart cannot be obtained with these techniques.

The present study provides the first clinical evaluation of a system with which two-dimensional cross-sections of the heart were recorded in real time with good resolution at 80 frames a second. Cardiac structures are visualized in their true anatomical relations and important functional information is obtained. In this paper, the examination techniques and the clinical applications of the system will be described in more detail.

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Methods

The technical aspects of the multiple element echo system[1] have been described in detail in previous papers (Bom *et al.*, 1971, 1973a; Bom, 1972; Roelandt *et al.*, 1973). The core of the system consists of an 8 cm linear array of 20 fixed ultrasound elements. From each element,

[1] ECHOcardioVISOR 01, Organon Teknika, Oss, The Netherlands.

the video signal of the returning echoes is converted to intensity or brightness dots (B-mode) and displayed on the horizontal axis of the oscilloscope. The anterior chest wall is always to the left on the display. The location of the signal from each element on the vertical axis of the oscilloscope corresponds to the position of the element in the transducer. Rapid electronic scanning of all elements and appropriate display of the echoes results in the instantaneous display of moving structures. Presently a 40 line oscilloscope image is produced by an 'interlacing' technique (alternating shift of 2 mm of the image) to provide a more pleasing image. This reduces the effective frame rate to 80 frames a second or half the original repetition rate. Patient identification symbols, the continuous electrocardiogram, and the cross-sectional image are displayed simultaneously on the oscilloscope face. By means of display of the electrocardiogram of the three preceding seconds at the bottom of each frame, the exact correlation with the cardiac cycle is achieved.

Depth calibration can easily be performed in the same way as with conventional echo systems using a calibrated perspex block. Markings on the oscilloscope screen allow adjustment to the approximate 8×16 cm viewing area. For the figures shown in this paper, a correction factor can be calculated, as the height of a frame always corresponds to 8 cm in the original recordings. The energy levels of the ultrasound in the system were measured in a water tank. Ultrasonic intensity is usually expressed as average intensity in watts per cm^2; the average acoustic intensity was found to be 0·6 mwatts/cm^2 at 2·25 MHz. At 4·5 MHz it was 2 mwatts/cm^2. Both were measured 6 cm in front of the centre of the transducer in a water tank. Peak intensity was measured to be 0·7 watts/cm^2 and 3·6 watts/cm^2, respectively. These intensities are well within recognized limits of safety (Woodward, Pond, and Warwick, 1970; Ulrich, 1971).

Recording techniques

While the best images are those directly available on the oscilloscope display at the time of study, permanent records are required for subsequent analysis. However, production of a 'hard copy' of the same quality as the original study poses serious problems. In our laboratory, several recording methods are used and have been assessed for specific applications.

Magnetic videotape

For routine studies, all data are stored on magnetic videotape which allows playback for motion studies later. It was found that about 30 per cent of the quality of the original image is lost in the process. This is chiefly because of the rather slow frame speed of the video system as compared to the multiscan frame rate and the time-constant and limited sensitivity of the video camera. Motion, however, is preserved though the details of finer structures, such as valve cusps, may be lost.

Cinematographic film

The original oscilloscope image can be recorded on 16 mm and 35 mm cine film. However, since the camera speed is less than the frame rate of the multiscan, the echo dots are superimposed on one film frame. This results in smearing. Increasing the film speed to 80 frames per second creates problems with film exposure time and synchronization. The quality of the images is good when viewed in motion but the quality of each individual frame is poor. However, interpretation and qualitative assessment of left ventricular dynamics is quite possible with the cine film recordings.

Polaroid photographs

Single frame photographs can be made from the oscilloscope screen by Polaroid camera. Their quality is reasonably good for quantitative measurements. Triggering from the QRS complex allows the recording of frames at selected moments in the cardiac cycle, such as end-systole and end-diastole. Polaroids are presently used for outlining the left ventricle and calculation of volumes. Furthermore, they are quite suitable for documentation of specific anatomical abnormalities but, with this recording technique, motion is not preserved. Most of the figures included in this paper are Polaroid photographs.

Individual element recording

The signal from any selected element of the multiscan transducer can be recorded on the line scan recorder[1] in the M-mode. This combines the two-dimensional orientation facility of the multiscan with single element recording and facilitates measurements on selected lines of which the position through cardiac structures is known. The resolution and definition of specific echoes is comparable to conventional single element M-mode recordings.

Line scan records

Complete frames can be recorded on the line scan recorder.[1] The format of these images is small (19×40 mm), being limited by the recorder paper speed. An increase in size of the images by a factor of 2 would call for increase of recorder paper speed from 500 to 1000 mm/sec in order to keep the cross-sectional geometry correct. However, definition of the echoes is good and this recording technique is most promising. These 'postage stamp size' pictures are recorded at 25 frames a second simultaneously with the electrocardiogram.

Examination technique

Position of patient

Patients are examined in the supine position, with the head of the bed raised about 20° to 30°. A change in the position of the patient occasionally enhances the images. In our experience, turning the patient slightly on his left side allows better visualization of the interventricular septum and left ventricular posterior wall simultaneously. This is especially important for dimensional measurements and the outline of the left ventricle for the calculation of left ventricular volumes.

[1] Honeywell 1856 Visicorder.

Transducer positions

The transducer can either be held in a fixed position on the chest or a scanning movement can be performed. It is clear that the exact position and direction of the probe will differ from patient to patient and the described technique is only applicable when no significant changes in the configuration or position of the heart are present. A routine multielement echographic examination should always consist of displaying the long-axis cross-section first, followed by a transverse cross-section through the left ventricular cavity and a transverse scan.

Long-axis or oblique position In this position, the transducer is placed obliquely to the left of the sternum with the upper end at the costosternal border. The lower end is angulated laterally about 25° from the midline. This produces a cross-section through the long axis of the heart in a sagittal plane from the base of the heart toward the apex (Roelandt *et al.*, 1973; Kloster *et al.*, 1973a). When the probe is pointed straight posteriorly, the aortic root is the first structure identified in the upper part of the screen. Slight tilting of the probe to the right or left establishes that position in which both the aortic root and the cusps are seen. In this position the left atrium is posterior and part of the right ventricular cavity and/or pulmonary outflow tract are anterior to the aorta. The anterior leaflet of the mitral valve can be seen as it extends downward in direct continuity with the posterior aortic wall (mitral-aortic continuity). The interventricular septum is usually less clearly identified as the structure which extends directly from the anterior aortic wall (septal-aortic continuity) into an anterior direction. Improved definition of the wall of the left atrium and the posterior wall of the left ventricle can be obtained when the transducer is aimed to the patient's left. When the probe is slightly directed to the right of the patient, the interventricular septum, right ventricular cavity, and pulmonary outflow tract can be better seen.

Transverse position and scan In the transverse position the transducer is placed to the left of the sternum perpendicular to the long-axis position and approximately along the 3rd or 4th intercostal space. The upper end of the transducer is to the patient's right and forms the top of the image on the oscilloscope. The resulting image is a transverse cross-section through both the right and left ventricle at a $\pm 90°$ angle with the long axis of the heart (Roelandt *et al.*, 1973; Kloster *et al.*, 1973a). The left ventricle is posterior to the right ventricle with the interventricular septum at a slight angle from the upper right to the lower left. By tilting the transducer in a superior or an inferior direction, a two-dimensional transverse scan of the heart along the long axis can be performed (Fig. 1). A tilt in a superior direction establishes that position where the cross-sections of the right and left ventricles are largest and where the interventricular septum is best defined (Fig. 2A). The anterior leaflet of the mitral valve can be identified by its movement in the left ventricular cavity. Directing the probe slowly superiorly shows the interventricular septum merging into the anterior aortic wall (septal-aortic continuity) and the anterior leaflet of the mitral valve into the posterior aortic wall (mitral-aortic continuity). In the transverse cross-section when the base of the aorta is seen, the left atrium is sometimes clearly outlined posterior to the aorta (Fig. 2B). During this scan, the anterior tricupsid valve often becomes visible in the cross-section just below the aorta. In infants, where calcified structures in the anterior chest give no impediment to sound transmission, it is actually possible to displace the transducer stepwise from the apex towards the base and the great vessels, resulting in successive parallel cross-sections. The transverse scan and/or stepwise displacement of the transducer is very important for the diagnosis of congenital malformations, as cross-sectional anatomy can be assessed without any distortion.

Results

Up to the time of writing, 296 patients have been studied with the system. In the first 100 patients,

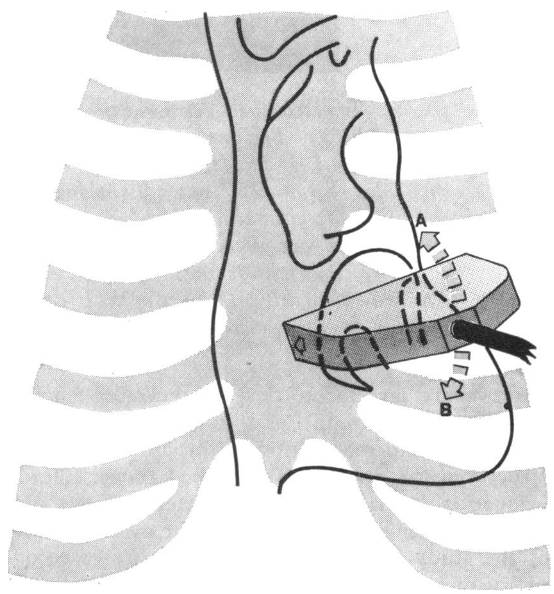


FIG. 1 *A schematic drawing of the transducer in the transverse position on the chest. The upper end of the transducer is to the patient's right and is the top of the cross-section displayed on the oscilloscope. By tilting the transducer a two-dimensional transverse scan along the long axis of the left ventricle is performed. The resulting image in position A is a transverse cross-section through both the right and left ventricle. In position B, the root of the aorta is visualized with the right ventricular outflow tract anterior and the left atrium posterior to it (see Fig. 2). During this scan a large part of the left ventricle can be studied and the septal-aortic and mitral-aortic continuity can be examined.*

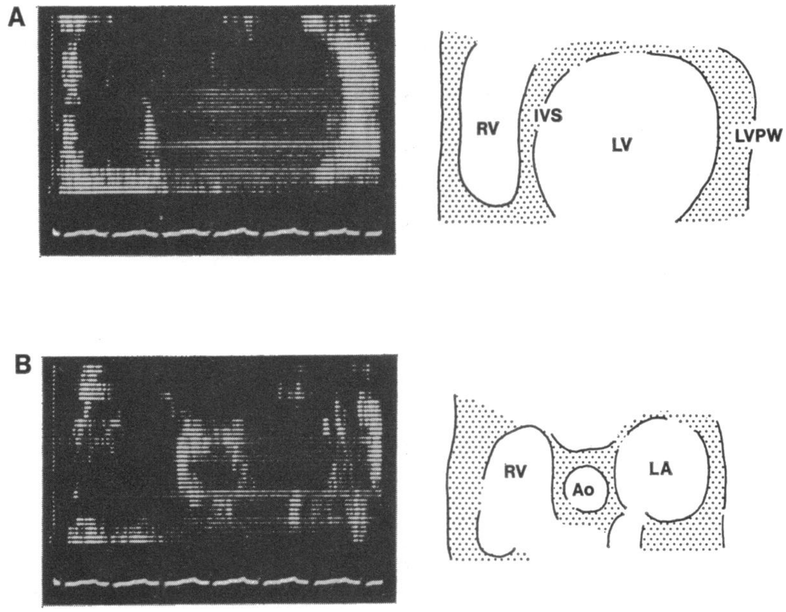


FIG. 2 *Two transverse cross-sections are shown with the transducer in positions A and B as shown in Fig. 1. The anterior chest wall is to the left. The resulting cross-section in position A is seen in panel A. The left ventricle (LV) is posterior to the right ventricle (RV) with the interventricular septum (IVS) at a slight angle from the upper right to the lower left. (LVPW = left ventricular posterior wall.) The lower cross-section is obtained with the transducer in position B (Fig. 1). The root of the aorta (Ao) is clearly delineated with the left atrium (LA) posterior and part of the right ventricle (RV) anterior to it. The cross-sections were obtained in a patient with cardiomyopathy. The size of the left ventricle is enlarged and there is also left atrial enlargement due to mitral incompetence.*

efforts were directed to develop the most efficient examination technique and to establish standard views for rapid recognition of the different cardiac structures and cavities, as described above. Clinical evaluation forms were used to determine the capabilities of the system, including the overall quality of the study, the frequency and quality of recognition of specific structures, and the possibility of making a clinical diagnosis from the oscilloscope display. The results are described in detail elsewhere (Roelandt *et al.*, 1973; Kloster *et al.*, 1973a; Bom *et al.*, 1973b). In brief, good or excellent studies with satisfactory recognition of the mitral and aortic valves and left ventricular walls were possible in over two-thirds of all adults and in nearly all infants and children. Specific cardiac diagnoses could be made in about 40 per cent of patients.

Applications of system in diagnostic cardiology

Normal cardiac cross-sections The cross-section of the heart obtained by the multiscan with the probe in the oblique position is the same as that plane through which the single element is rocked when one performs a sector scan from the apex towards the base of the heart (Feigenbaum, 1972). However, these structures are now visualized two-dimensionally in their true anatomical relations and in real time motion. Such a cross-section is shown in Fig. 3 in diastole and systole. The anterior and posterior aortic walls present as two parallel echoes which move anteriorly during systole and posteriorly during diastole. The sinuses of Valsalva can usually be outlined and the cusps are seen centred in the aortic root in diastole. In the best studies they can be followed during opening and throughout systole as well. As the left atrium is posterior to the aorta and its dimension normally never exceeds that of the aorta, confusion with this structure is impossible. The anterior leaflet of mitral valve is a direct continuation of the posterior aortic wall (mitral-aortic continuity) and terminates in the region of the posterior papillary muscle. Therefore, the anterior leaflet of the mitral valve is usually best seen with the probe in the long axis position. It

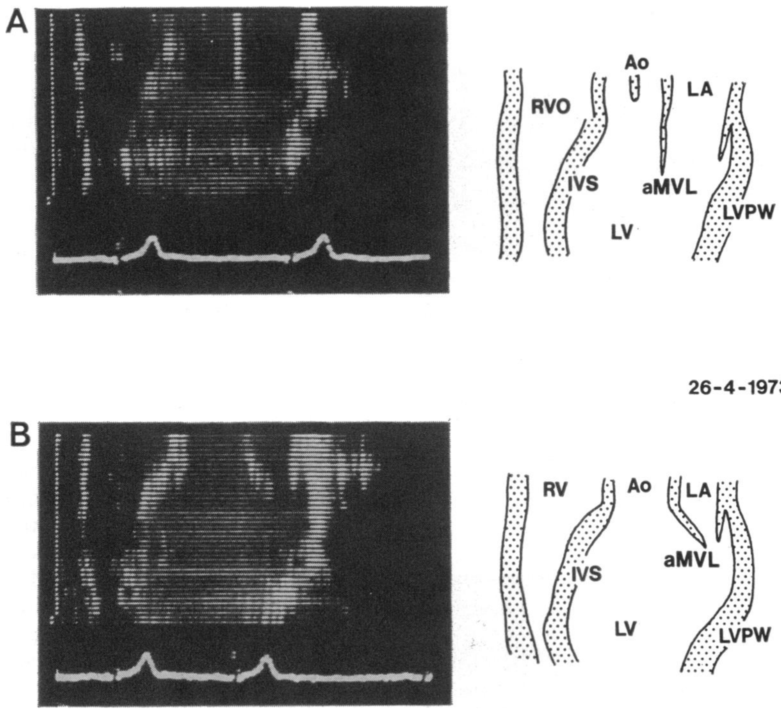
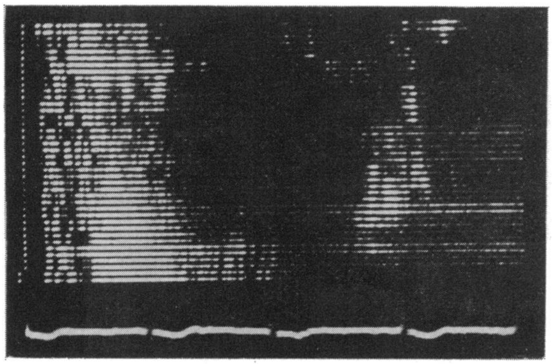


FIG. 3 *End-diastolic (A) and early systolic (B) long-axis cross-sections are shown. For orientation see diagrams. The aortic root (Ao) is seen in the upper centre with the cusps visible in diastole. The right ventricular outflow tract (RVO) is anterior to the aorta and the left atrium (LA) posterior to it. The interventricular septum (IVS) is in continuity with the anterior aortic wall (septal-aortic continuity) and the anterior mitral valve leaflet (aMVL) with the posterior aortic wall (mitral-aortic continuity). The anterior mitral valve (aMVL) in diastole is in an open anterior position and in a posterior and superior position when closed in systole. The right end of the electrocardiographic tracing indicates the position of the cross-section in the cardiac cycle. (LV = left ventricle; LVPW = left ventricular posterior wall.)*

appears as a thin, freely moving structure which travels anteriorly in early diastole, closes partially, then reopens during atrial contraction. During systole, closure of the mitral valve takes place primarily by a posterior and superior movement of the anterior leaflet of the mitral valve against the posterior leaflet. It is difficult to define the free edge of the anterior leaflet as it often appears as a continuous structure from the posterior aortic wall to the posterior papillary muscle, including the chordae. The motion of the posterior leaflet of the mitral valve varies between individuals, but is always much shorter, less mobile, and moves in the opposite direction from the anterior leaflet in diastole. The interventricular septum is in continuity with the anterior aortic wall (septal-aortic continuity). In general, the left side of the interventricular septum is clearly seen whereas the right side may only be definable when some right ventricular enlargement is present. The left ventricular epicardium and pericardium are the best reflectors for ultrasound of the heart and the left ventricular posterior wall is clearly delineated posteriorly by these echoes. Anterior to these, multiple echoes are seen which represent myocardium and endocardium. This was verified by recording the echoes of each line of the multiscan in time-motion on the line scan recorder.

The cavity of the right ventricle and the pulmonary outflow tract are only well delineated when right ventricular hypertrophy or dilatation is present. Of great importance is the study of the movement of the left ventricular wall. The long-axis cross-section closely resembles the outline of the left ventricular cavity as seen on the left ventricular angiograms in the right anterior oblique position. Therefore, it is possible to analyse the contraction

END-DIASTOLE



END-SYSTOLE

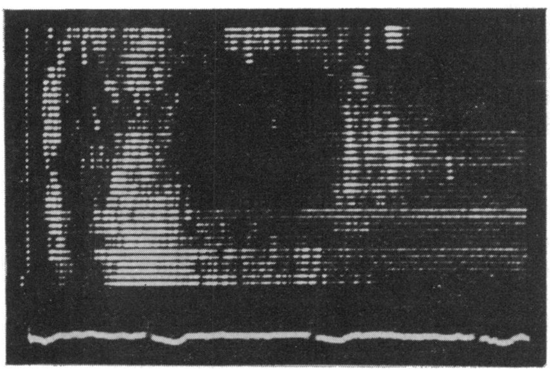


FIG. 4 *Transverse cross-sections in end-diastole and end-systole in a normal individual are shown. The left ventricular cavity is clearly outlined. Motion of the ventricular walls in this cross-section was symmetrical and this could easily be assessed on the oscilloscope display.*

pattern and motion of the septum and posterior left ventricular walls. Furthermore, with the transverse scan, the contraction of the left ventricular myocardium can be studied in different cross-sections and a greater percentage of the left ventricle is accessible for wall motion analysis than with conventional angiographic techniques. By way of example, Fig. 4 shows a diastolic and systolic transverse cross-section of the left ventricle. Though in this single frame representation real-time motion is lacking, the symmetrical contraction of the left ventricle is clearly shown.

Valvular heart disease In mitral stenosis alterations are seen in mobility and thickness of the anterior leaflet of the mitral valve. In mild mitral stenosis the anterior leaflet appears stiff, and motion is jerky and decreased in amplitude. There may even be anterior diastolic bulging. With severe stenosis the leaflets are fixed and the entire valve moves as a unit (Fig. 5, 6, and 7). Except for some cases with mild mitral stenosis, one sees the posterior leaflet of the mitral valve moving in the same direction with the anterior leaflet in diastole instead of in the opposite direction, as occurs, normally. A fibrotic and/or a calcific valve is indicated by dense, thickened echoes most apparent in the anterior leaflet (Fig. 5, 6, and 7). The enlarged left atrial cavity is usually well delineated; its cross-sectional dimension is larger than the aortic diameter and the increase is proportional to the degree of enlargement (higher LA/Ao ratio) (see Fig. 5, 6, and 7). With pulmonary hypertension, the right ventricular cavity is enlarged and the tricuspid valve becomes visible. The presence of concomitant mitral regurgitation in patients with mitral stenosis cannot be diagnosed with the multiscan system. However, in some cases with predominant mitral regurgitation, an increased excursion of the anterior leaflet of mitral valve is seen. The presence of an enlarged left atrium together with an increased left ventricular volume supports further the diagnosis of mitral regurgitation.

An exaggerated movement of the amplitude of the anterior leaflet of the mitral valve is seen in patients with prolapsing mitral valve syndrome during diastole. Actual prolapse in systole of the anterior leaflet past the posterior leaflet has been seen in two patients. The posterior leaflet of the mitral valve rarely shows this excessive movement. Thickening, calcification, and decreased mobility of the cusps can readily be seen in aortic valve disease (Fig. 5, 6, and 7). In severe calcific aortic stenosis, the valve appears as a series of dense, thick echoes in diastole which separate incompletely during systole. In mild aortic stenosis, either an immobile anterior (right coronary) cusp or posterior cusp can be seen (Fig. 7). Concomitant features are poststenotic dilatation of the aorta and increased left ventricular wall thickness.

Coronary artery disease A general qualitative assessment of the state of left ventricular function can be made immediately from cardiac size, shape, and wall motion. In general an enlarged left ventricle has a more round geometric shape while its dimensions are increased. The motion pattern can be studied, and localized or generalized disorders of contraction detected. The sagittal long-axis cross-section shows the interventricular septum and the

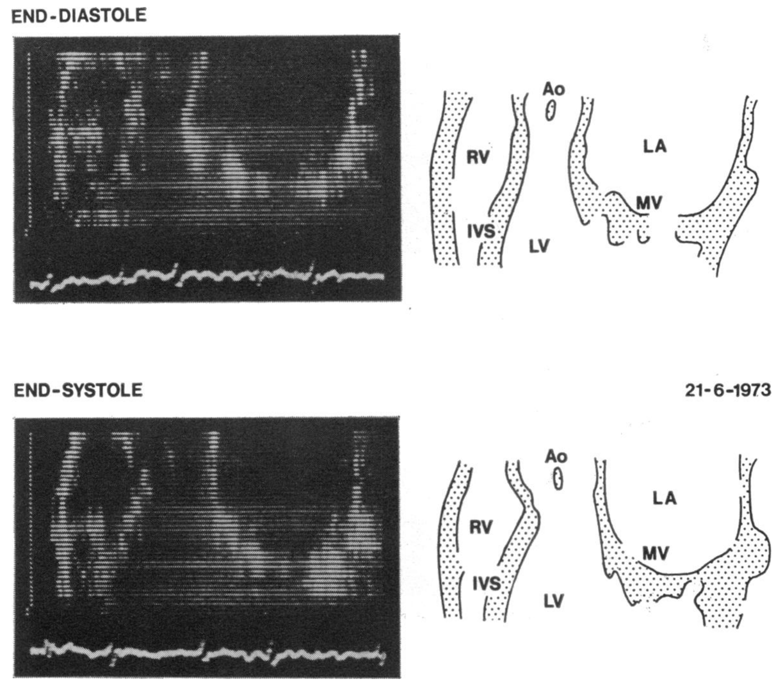


FIG. 5 *End-diastolic and end-systolic frames in a patient with severe calcific aortic and mitral stenosis. Both the anterior and posterior mitral valve leaflets are fixed and the entire valve (MV) moves as a unit, anteriorly in end-diastole, and posteriorly in end-systole. The immobilized calcified aortic valve remains visible during the whole cardiac cycle in the middle of the aortic (Ao) root. (RV = right ventricle; LV = left ventricle; IVS = interventricular septum.) The left atrium is extremely large.*

left ventricular posterior wall. By transverse scanning along the long axis, extensive sections of the left ventricle become accessible for study. Most difficult to display are the apex and part of the anterior wall merely because they are outside the pericardial window. Regional akinesis, hypokinesis, or dyskinesis can be recognized when the behaviour of these areas is compared to the normal or exaggerated contraction of the rest of the left ventricle. Furthermore, quantitation of left ventricular volumes and calculation of ejection fractions is possible with the area-length method.

Congenital heart disease Since cardiac structures and their relations are visualized without distortion with the multiscan technique, cross-sectional anatomy can be assessed. This makes the diagnosis of congenital malformations a major potential application. Thus far, however, our experience has been limited. Mitral-aortic and septal-aortic continuity or discontinuity and the size and orientation of the great vessels relative to the position of the ventricles are visualized, providing important information in many forms of complex cyanotic congenital malformations. Septal overriding of an enlarged aorta has been observed in patients with tetralogy of Fallot.

In patients with small left-to-right shunts no specific abnormalities were seen. With larger shunts, however, enlargement of the right ventricular chamber because of the volume overload becomes apparent. The most specific changes are related to the interventricular septum. The interventricular septum commonly runs posteriorly instead of anteriorly from the aortic root in the presence of a significant shunt lesion (Fig. 8). Systolic anterior or paradoxical septal motion has been described as a reliable finding in right ventricular overload and can be seen clearly with the multiscan display. We have the impression that the paradoxical motion never involves the whole intraventricular septum. The upper part moves always anteriorly and the

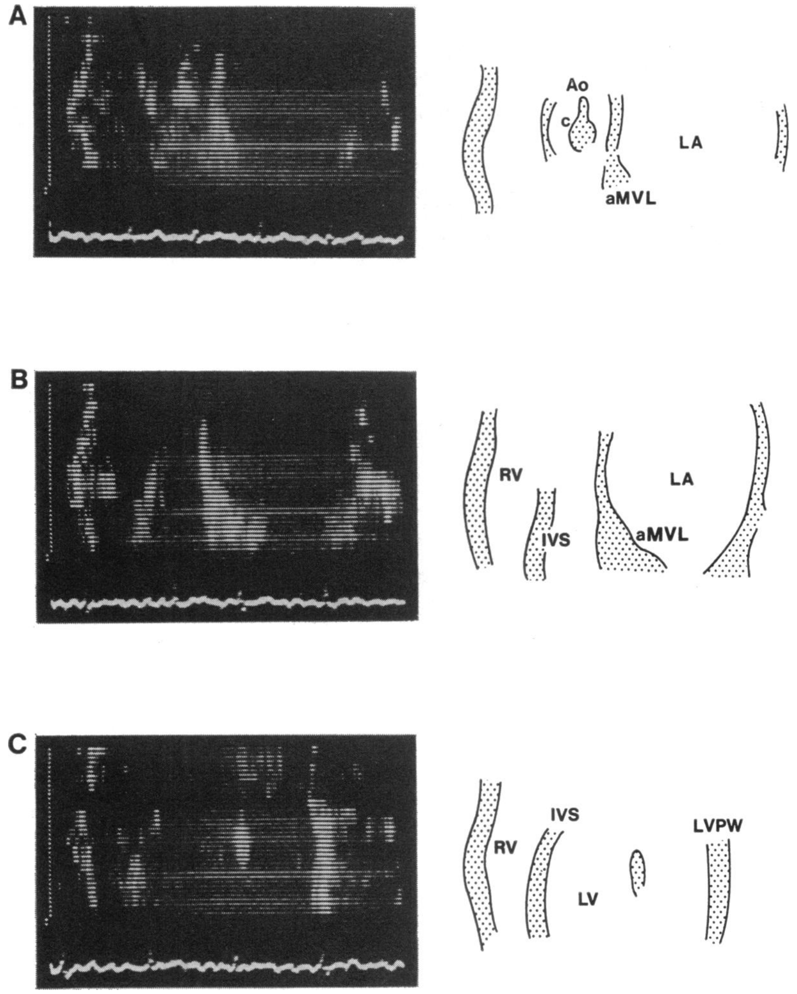


FIG. 6 *A transverse scan in the same patient as shown in Fig. 5. Panel A shows that cross-section where the root of the aorta (Ao) is visualized with a dense thickened echo of the calcified cusps (c). Part of the calcified anterior mitral valve (aMVL) is seen in continuity with the posterior aortic wall. The much enlarged left atrium (LA) is visualized posterior to the aorta. In an intermediate position (panel B), the interventricular septum (IVS) is seen at the same depth as the anterior aortic wall in panel A demonstrating septal-aortic continuity. There is a dense thickened anterior mitral valve echo (aMVL) and the left atrium is still visible at this level. Further tilting of the transducer (see position A in Fig. 1) shows a cross-section through both the right ventricle (RV) and left ventricle (LV). A dense echo, most probably of calcified chordae, is visible in the left ventricular cavity.*

lower part posteriorly. The point around which the interventricular septum pivots is lower in the septum when larger shunts are present but no systematic study has been undertaken yet. In all patients with right ventricular chamber enlargement, the tricuspid valve is visualized and has increased motion amplitude. In the record shown in Fig. 8 the pulmonary cusps were visualized also.

Cardiomyopathies In the hypertrophic types, recently unified and described as asymmetrical septal hypertrophy (Henry, Clark, and Epstein,

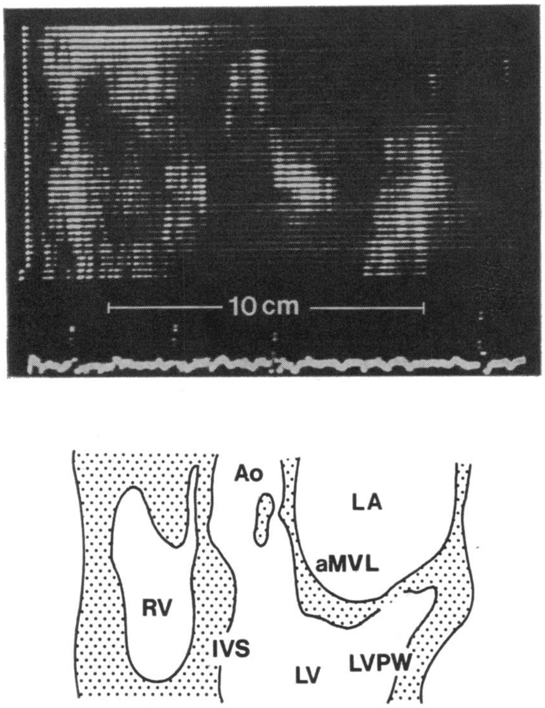


FIG. 7 *Long-axis cross-section in another patient with calcific aortic and mitral valve disease. A dense echo of the posterior coronary cusp of the aorta remains visible during systole. (RV = right ventricle; IVS = interventricular septum; Ao = aorta; LA = left atrium; aMVL = anterior mitral valve leaflet; LV = left ventricle; LVPW = left ventricular posterior wall.)*

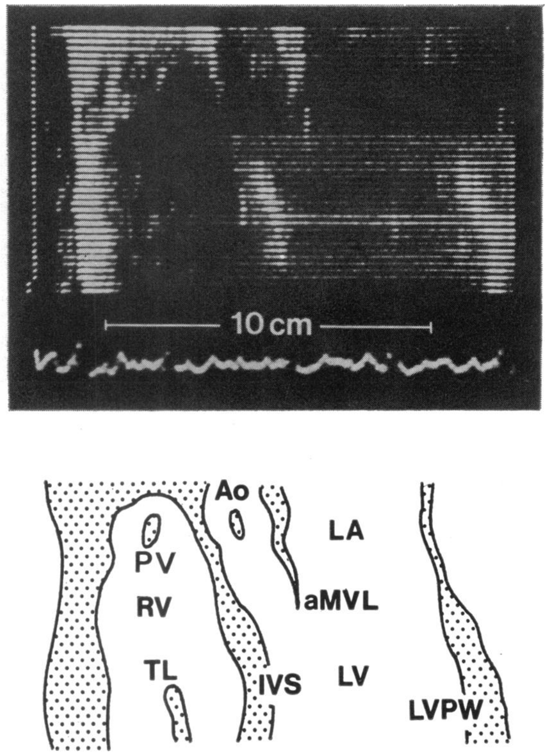


FIG. 8 *A long-axis cross-section in a patient with atrial septal defect (secundum type) and pulmonary hypertension. A greatly dilated right ventricle (RV) is apparent and the movements of both the tricuspid valve (TL = tricuspid leaflet) and pulmonary valve (high in the right ventricle) were seen on the oscilloscope display. The structures were identified by their typical motion pattern on the M-mode recordings made from the selected single elements passing through these structures. The interventricular septum (IVS) runs posteriorly instead of anteriorly as seen normally (see Fig. 3). This is a common finding with right ventricular dilatation. Note also the enlarged left atrium (LA). (Ao = aorta; aMVL = anterior mitral valve leaflet; LV = left ventricle; LVPW = left ventricular posterior wall.)*

1973), the most apparent features are increased thickness of the interventricular septum and a banana-like shape of the small-sized left ventricle. Motion of left ventricular walls is normal or even exaggerated. An enlarged left atrium points to coexistent mitral regurgitation. Where abnormal systolic motion of the anterior leaflet of the mitral valve was present, it resulted in a narrow left ventricular outflow tract in those patients in whom an outflow gradient was found during left ventricular heart catheterization. Fig. 9 shows the typical appearance of the multiscan echocardiogram in a patient with asymmetrial septal hypertrophy and a left ventricular outflow gradient. Asymmetrical septal hypertrophy is an instance which strikingly illustrates the unique qualities of the multiscan for instantaneous and complete diagnosis. In the dilated or congestive types of cardiomyopathies a large left ventricle of globular shape with generalized hypokinesis is so characteristic that the diagnosis is made immediately (Fig. 2 and 10). The increased distance between the anterior leaflet of the mitral valve and the interventricular septum in contrast to the decreased distance in the hypertrophic types is another characteristic finding. In all patients studied the left atrium was greatly enlarged (Fig. 2).

Pericardial effusion A few patients with pericardial effusion were studied. Small amounts of fluid, detected with the single element technique as

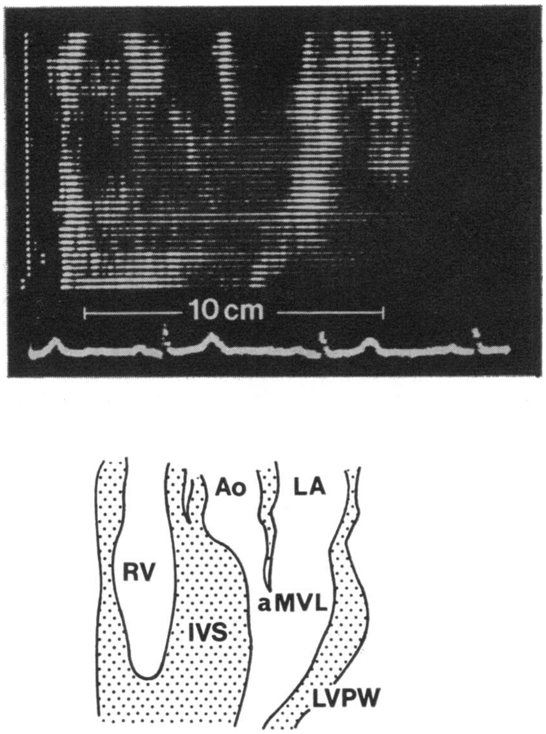


FIG. 9 *The typical features found in patients with asymmetrical septal hypertrophy are seen on this cross-section. The thickened septum (IVS) as compared to the left ventricular posterior wall (LVPW) is clearly shown and the banana-like shape of the left ventricle is striking. The frame shows a systolic cross-section and the anterior mitral valve leaflet (aMVL) is in an abnormal anterior position, close to the interventricular septum instead of in a posterior and superior position as seen normally. This causes narrowing of the left ventricular outflow, and in this patient an outflow gradient of 60 mmHg at rest was measured during cardiac catheterization.*

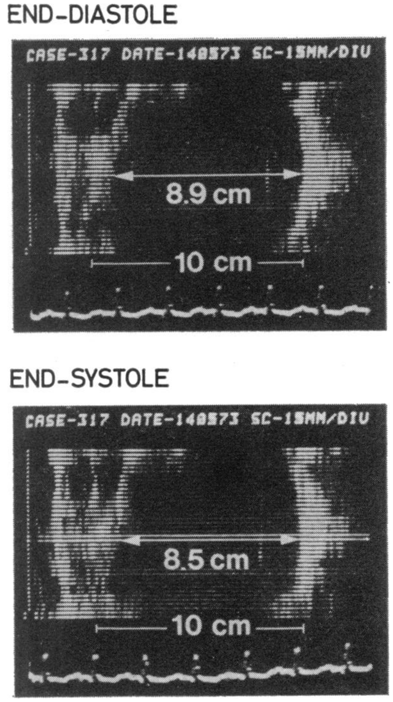


FIG. 10 *End-systolic and end-diastolic long-axis cross-sections obtained from a patient with a dilated congestive cardiomyopathy. An extremely large ventricle of a globular shape is seen. Generalized hypokinesis was immediately diagnosed from the oscilloscope display and is here shown by the small changes of a left ventricular dimension between end-diastole and end-systole (8·9 cm vs. 8·5 cm).*

an echo free space between posterior epicardium and pericardium during systole, were not visualized with the multiscan. Larger amounts, seen on the M-mode as an anterior and a posterior echo free space, were always detected with the multiscan. An example is given in Fig. 11. This patient had massive pericardial effusion and a large amount of fluid in the anterior pericardial space. In this case, an oscillating anterior-posterior movement of the whole heart in the pericardial fluid was seen. This total cardiac displacement has been described as a common finding when large pericardial effusions are present (Feigenbaum, Zaky, and Grabhorn, 1966).

Applications for quantitation and dimensional measurements

In a first attempt to employ the system for quantitative analysis, a comparison was carried out in 23 patients of the aortic root diameter measured from calibrated angiograms and from videotape recordings of multiscan images. A significant correlation was found ($P < 0{\cdot}001$, χ^2 test) with a small standard error (Kloster *et al.*, 1973a). When the interventricular septum and left ventricular posterior wall are visualized and recorded simultaneously, dimensional analysis of the left ventricle is possible. On records from the line scan recorder with a selected single line passing through the left ventricular cavity good definition of the left side of the interventricular septum and the posterior left ventricular endocardium is usually obtained (Fig. 12). By selection of the most representative diameter of the left ventricle, it should also be possible to calculate the

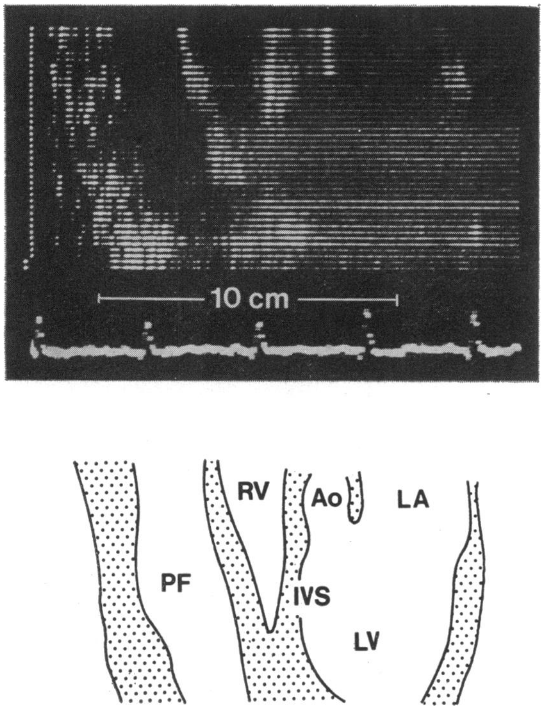


FIG. 11 *In this patient with massive pericardial effusion, a large echo-free space is recognized anterior to the heart. (PF = pericardial fluid.) The whole heart was displaced and the posterior heart wall was at a depth of about 16 cm. On the oscilloscope display, an oscillating movement of the entire heart was demonstrated.*

rate of midwall circumferential fibre shortening, as suggested by Paraskos *et al.* (1971) and Cooper *et al.* (1972). In addition, data on cardiac volumes with the echocardiographic formulae proposed by Popp and Harrison (1970), Pombo, Troy, and Russell (1971), and Feigenbaum *et al.* (1972) should be obtainable. As it is also possible to record both the endocardium and pericardium separately, by changing the depth gain compensation, measurements of left ventricular posterior wall and interventricular septal thickness come within reach (Fig. 12). However, since multiscan provides instantaneous left ventricular cross-sections suitable for the calculation of left ventricular volumes from generally accepted and anatomically correct angiographic formulae, this approach was first pursued (Greene *et al.*, 1967; Sandler and Dodge, 1968). When the whole left ventricle is visualized it proved possible to measure the long axis and to outline the left ventricular cavity. Fig. 13 shows an end-diastolic and end-systolic frame used for these measurements. To assess the possibilities and feasibility of this method, left ventricular volumes calculated from multiscan frames and quantitative left ventricular angiograms have been compared in 14 patients.

Multiscan end-diastolic volume showed a high degree of correlation with angiographic volumes (mean values 90·4 versus 95·9 ml/m^2; r = 0·92). However, end-systolic volumes determined by multiscan were consistently larger than those determined by angiography (56·2 versus 44·5 ml/m^2; r = 0·89), so that the stroke volume by multiscan was consistently smaller. As a result the left ventricular ejection fraction by multiscan as compared to that by angiography is lower. This was also found with other techniques of volume measurement which similarly indicate that assessment of end-systolic volume by angiography shows a systematic underestimation of volume (Bartle and Sanmarco, 1966; Hugenholtz, Wagner, and Sandler, 1968). The methods and results will be discussed elsewhere in greater detail (Kloster *et al.*, 1973b).

Discussion

At present there are many echocardiographic techniques available to obtain two-dimensional information about the heart. All techniques based on B-scan (Ebina *et al.*, 1967; Kikuchi and Okuyama, 1970; King, 1973) produce 'frozen' images of the heart at a selected part of the cardiac cycle. As many cardiac cycles are required to construct the image, changes in cardiac position and difficulties caused by irregularities in rhythm render these systems suboptimal for clinical application. Åsberg (1967) obtained two-dimensional information with a mechanical mirror system rotated over an arc of about 30° at a rate of seven frames a second. Hertz and Lündström (1972) obtained 16 frames a second with a similar system. For these mechanical rocking systems limited scanning rates, bulky transducer size, difficult transducer aiming, and image distortion are some of the problems. Gramiak *et al.* (1972) developed a technique which produces ultrasonic cross-sectional images of the heart in motion. However, cine-ultrasound cardiography is time consuming and there is some image distortion as the wedge-shaped section of the heart obtained by the sound beam is represented in a rectangular format. None of these drawbacks pertains to the multiscan system presented here. Thus, the capabilities of diagnostic ultrasound are expanded by instantaneous two-dimensional moving cross-sections of the heart. Furthermore, when compared to the negative shadow images obtained with angiography, there is the advantage of a positive cross-section of the heart with all its structures visualized in a manner familiar

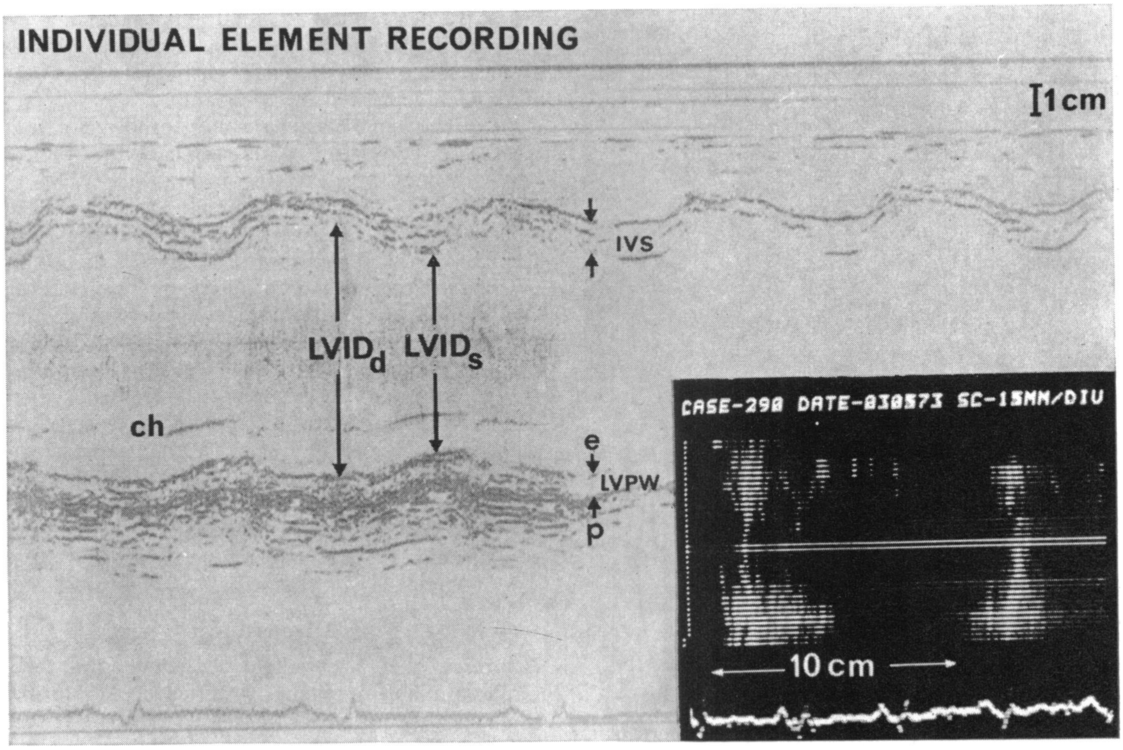


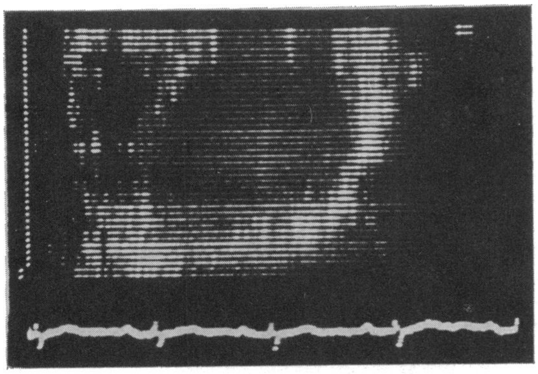
FIG. 12 *This M-mode tracing is recorded from a single element of the multiscan transducer. The selected signal is the bright line running through the left ventricular cavity, seen on the insert photograph. The patient has coronary artery disease with a hypokinetic posterior wall and an enlarged left ventricular cavity. Both the interventricular septum and left ventricular posterior wall are recorded with satisfactory resolution. Changing the time gain compensation allows measurements of interventricular septum and left ventricular posterior wall thickness. This record is most suitable for dimensional left ventricular measurements and calculation of derived volume data. ($LVID_s$ and $LVID_d$ = left ventricular internal dimension during systole and diastole; ch = chordae echo; e = endocardium; p = pericardium; IVS = interventricular septum, LVPW = left ventricular posterior wall.)*

to those who know cardiac anatomy. In addition, information on the relations of cardiac structures is provided without distortion.

Congenital malformations, especially in newborns and infants, offer a major potential application for the system particularly when the risk of unnecessary catheterization may be avoided by appropriate preselection of candidates by means of the echoscan. Qualitative valve motion analysis in valvular heart disease and evidence of thickening and/or calcification in cases with rheumatic mitral and aortic valve disease is immediately available. Furthermore, the size, shape, and contraction pattern of the left ventricle can be interpreted and a qualitative assessment of the left ventricular function made. Evaluation of left ventricular function and detection of localized disorders of wall motion in patients with coronary artery disease is a most promising area for investigation. When the long-axis cross-section and a transverse scan are performed, a large part of the left ventricle becomes accessible for study.

While the most unique application of the system is the study of the dynamics of cardiac contraction and valve motion, it allows also quantitative measurements of cardiac dimensions and left ventricular volumes. This is an area of major interest in clinical cardiology today. Despite the excellent correlations between echo and angio volumes found in some studies using the single element echocardiographic techniques, it is not known if the echo axis truly approximates the angiographic short diameter of minor axis of the left ventricle (Pombo *et al.*, 1971;

END-DIASTOLE



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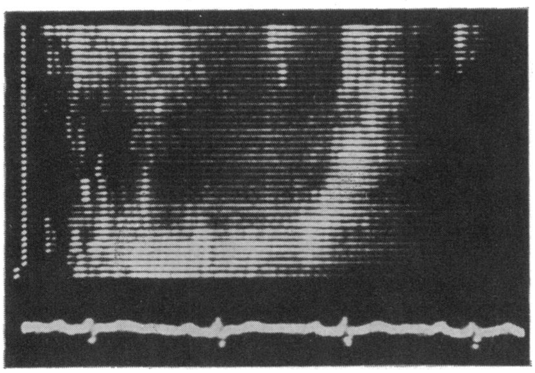

FIG. 13 *Examples of end-diastolic and end-systolic frames used for calculation of left ventricular volumes are shown. The cross-section resembles the left ventricular image obtained with angiocardiography in the right anterior oblique position but is a mirror image of it as the apex is to the left on the multiscan images. The aorta and mitral valves are clearly seen, and it is possible to outline the interventricular septum and the left ventricular posterior wall readily. Calculations of volumes are performed using the area-length method.*

Feigenbaum *et al.*, 1972). Indeed, to calculate the volume from echo-determined left ventricular dimensions, one has to assume that the measured dimensions have constant relations to the axes of the left ventricle both at end-systole and at end-diastole. This is not true for dilated ventricles and patients with segmental abnormalities of contraction due to coronary artery disease. The multiscan system appears to offer a ready solution, since the precise location of each echo axis through the left ventricle is known. As both the septal and posterior left ventricular endocardial echoes are displayed on M-mode recordings of a selected element from the transducer, this information is also present on the two-dimensional images (Fig. 12). Therefore a real cross-section of the left ventricle is obtained comparable to the shadow of the left ventricle during angiography in the right anterior oblique position. The area-length method proposed by Greene *et al.* (1967) can be applied and, since both length and area are measured, this method is applicable to ventricles of all sizes and shapes. The initial results of studies in 14 patients are encouraging. End-diastolic volumes calculated from multiscan frames agree well with angiographically calculated volumes. There is a consistent overestimation of the multiscan end-systolic volume compared to angio, resulting in a smaller stroke volume and an underestimation of left ventricular ejection fraction. However, a systematic underestimation of end-systolic volumes by cineangiography has been found with other indicator dilution methods (Hugenholtz *et al.*, 1968; Bartle and Sanmarco, 1966), and may simply reflect methodological differences. The fact that these qualitative analyses and quantitative measurements can be made in a non-invasive manner with an unlimited frequency opens new areas for clinical investigation as well as for teaching and training.

Some problems have still to be resolved in displaying and recording the multiscan information. Different display and recording methods are still under evaluation (Fig. 14). Considerable technical improvements in the instrument are also possible and will increase the capabilities of the system.

In general, the multiscan is subject to the same physical limitations of sound transmission and reflection as conventional single element systems (Bom, 1972; Bom *et al.*, 1973a). Significant distortion of images behind ribs because of higher ultrasound velocities in bone has not been observed. Insufficient lateral resolution, a problem of all echo systems, continues to be a limitation (Bom *et al.*, 1973a). Also echoes originating from side lobe beams can deform the display of specific structures. Though these side lobe effects were negligible in *in vitro* experiments, their overall effects in the clinical situation remain unpredictable (Bom, 1972), and practical experience will have to be collected before a definite statement as to their influence can be made. The commonest cause of failure is the presence of only a small pericardial window, for example, when pulmonary emphysema or an anterior chest wall deformation is present. Intervening dense tissue, such as heavily calcified ribs, may obscure

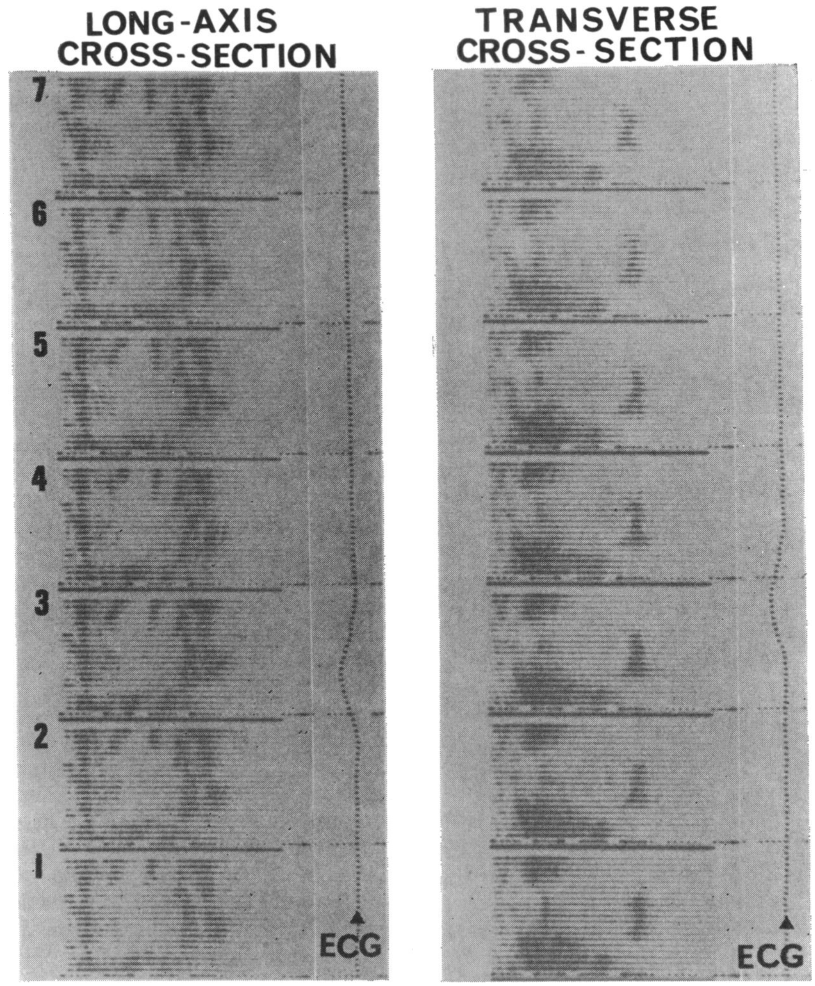

FIG. 14 *Seven cross-sections recorded on the Honeywell 1856 Visicorder with the transducer in the long-axis and transverse positions are shown together with the electrocardiogram. The format of the images is small but the definition of the echoes is quite good. These 'stampsize' pictures are recorded at 25 frames/sec.*

parts of the image. This factor is operative especially in elderly people. However, considerable detail remains visible between the obscured areas, and structures can be recognized by extrapolation. Difficult or unsatisfactory studies occur particularly with a large anteroposterior chest diameter resulting in greater distance of the structures from the probe.

From the results presented in this paper one may conclude that multiscan echocardiography is a valuable extension of the now widely accepted single element technique and will become a fundamental addition to non-invasive methods for the study of the normal and diseased heart.

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